Reducing Mid-Spatial Frequency (MSF) Errors with VIBE Finishing

Review of Two Phase I SBIR Projects
Outline for Phase II SBIR – contract started June 7th

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Work funded by NASA Phase I and Phase II SBIRs

Outline

- Introduction
  - Mid-Spatial Frequency (MSF) Errors
  - VIBE Technology
- Characterization of MSF Errors
- MSF Error Removal with VIBE

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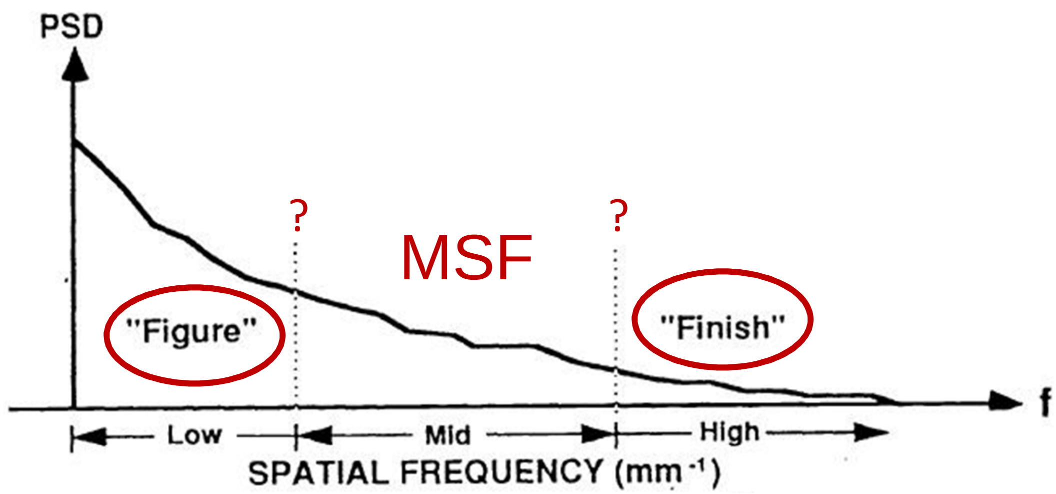
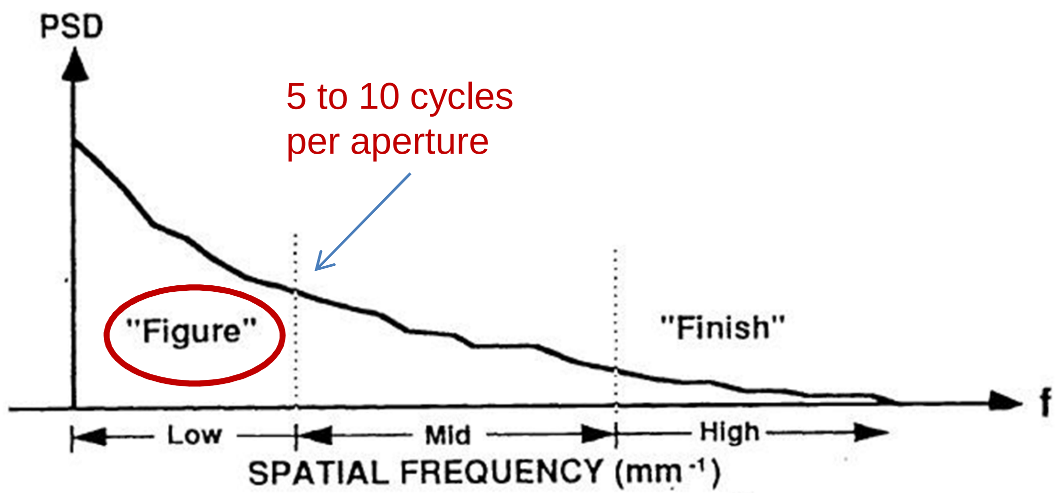
What is “mid-spatial frequency”?



J.E. Harvey and A. Kotha, “Scattering effects from residual optical fabrication errors, Proc. SPIE 2576-25

D. Aikens, J. E. DeGroote, and R. N. Youngworth, "Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems," (Optical Society of America, 2008).

Figure is the range of spatial frequencies addressable with a simple Zernike expansion



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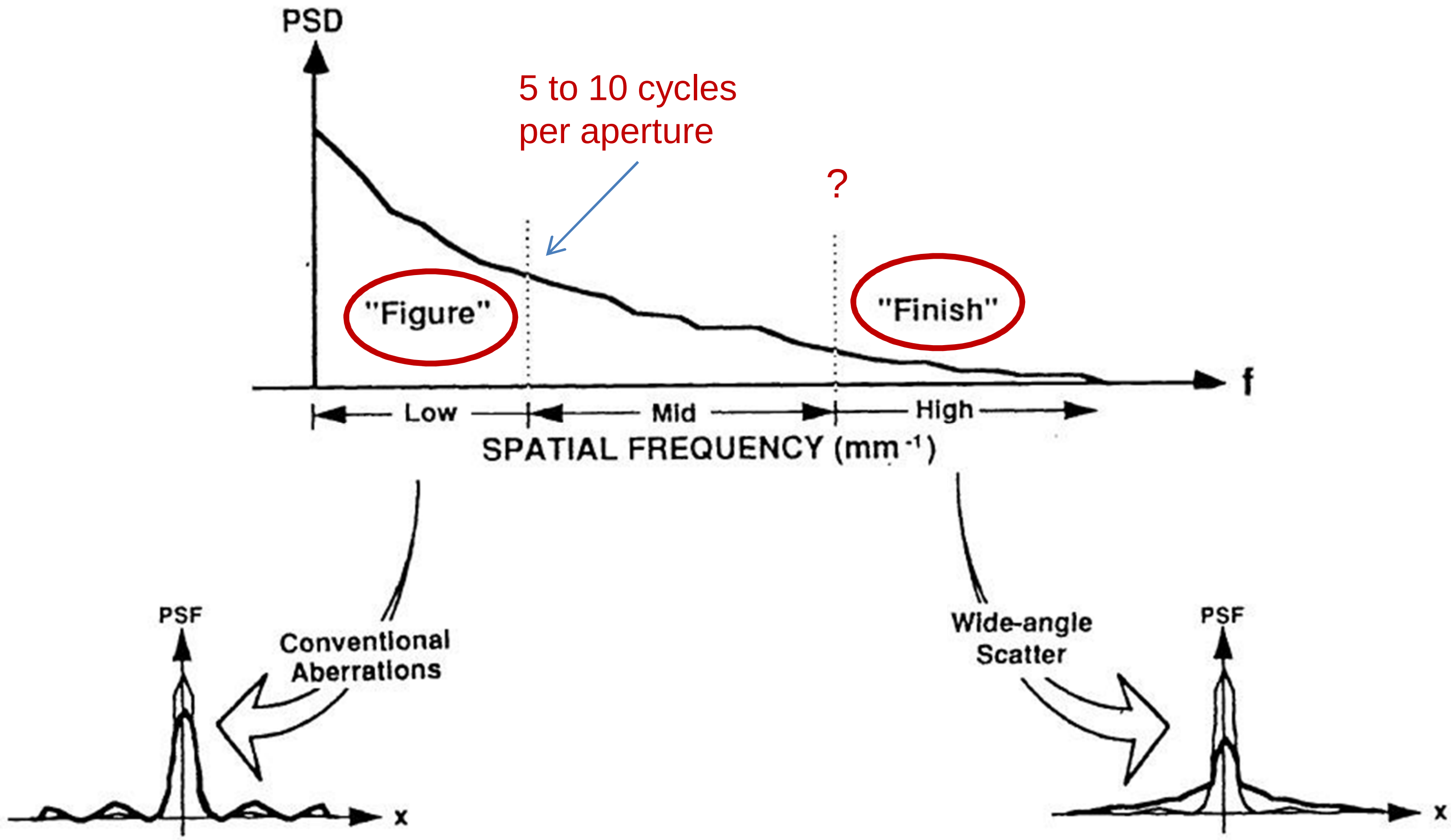
Finish (a.k.a "gloss" or "roughness") is typically less critical as it results in total transmission loss



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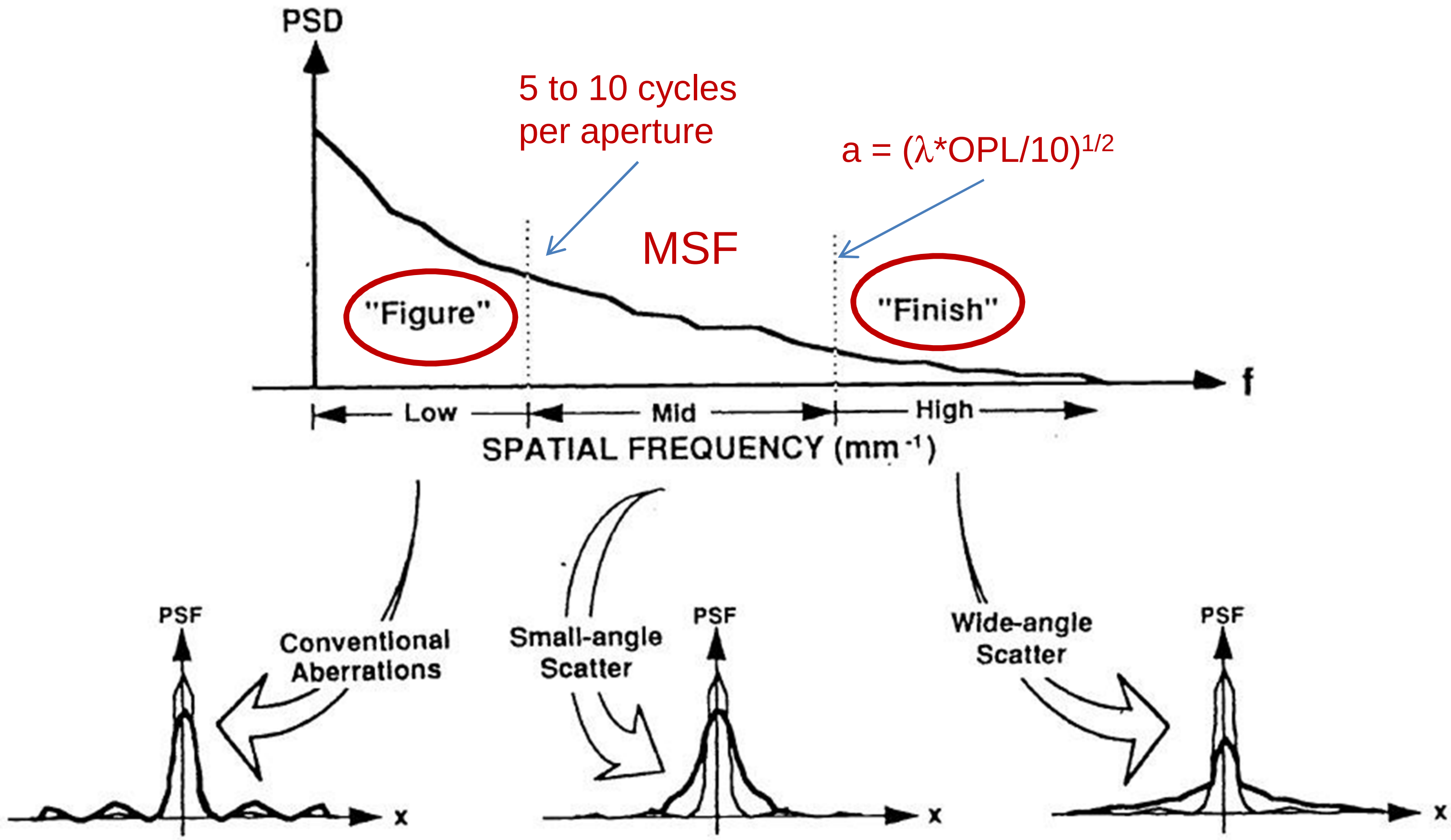
Mid-Spatial Frequency bandwith limits help to define the MSF itself



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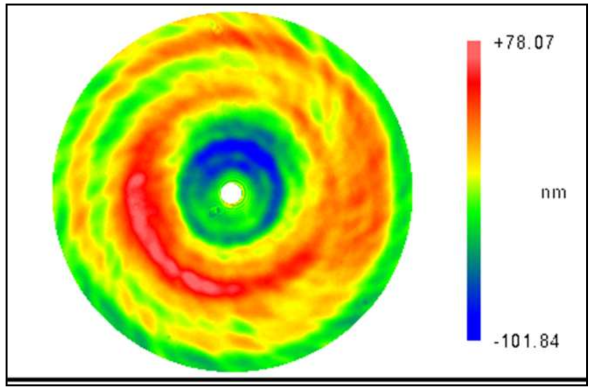
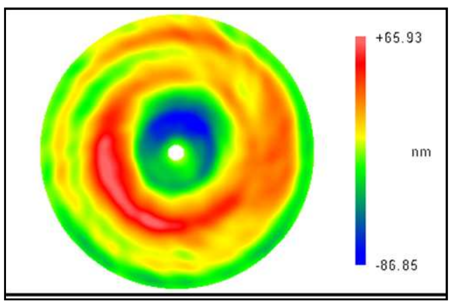
Example: Spoke and Spiral Errors

PV: 179.9nm
RMS: 28.6nm



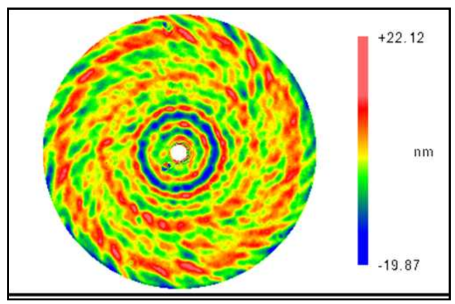
Unfiltered data

PV: 152.8nm
RMS: 26.3nm



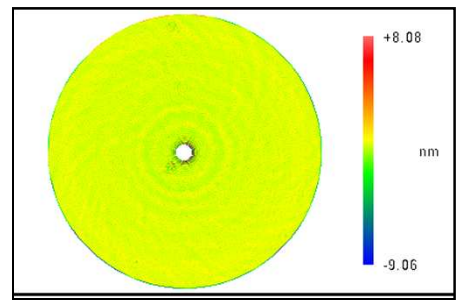
Low spatial frequency

PV: 41.9nm
RMS: 4.8nm



Mid-spatial frequency

PV: 17.1nm
RMS: 0.6nm



High spatial frequency

D. Aikens, J. E. DeGroote, and R. N. Youngworth, "Specification and Control of Mid-Spatial Frequency Wavefront Errors in Optical Systems," (Optical Society of America, 2008).

VIBE Process is a high-pressure, high-speed, full aperture polishing process

Optic slowly oscillates while in contact with vibrating lap

Full-aperture, conformal lap vibrates at high frequencies

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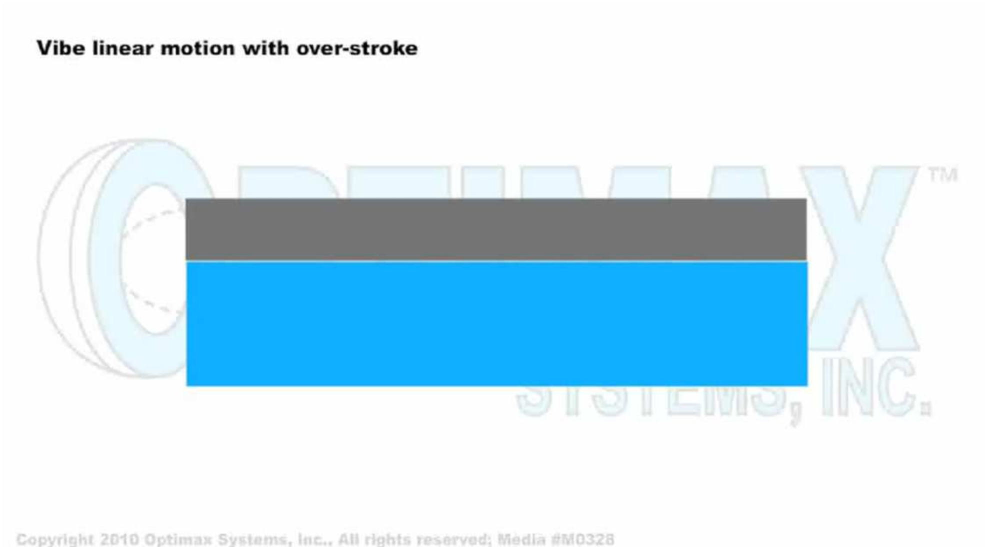
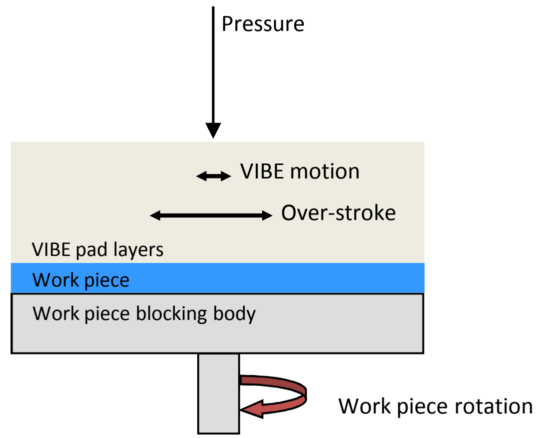
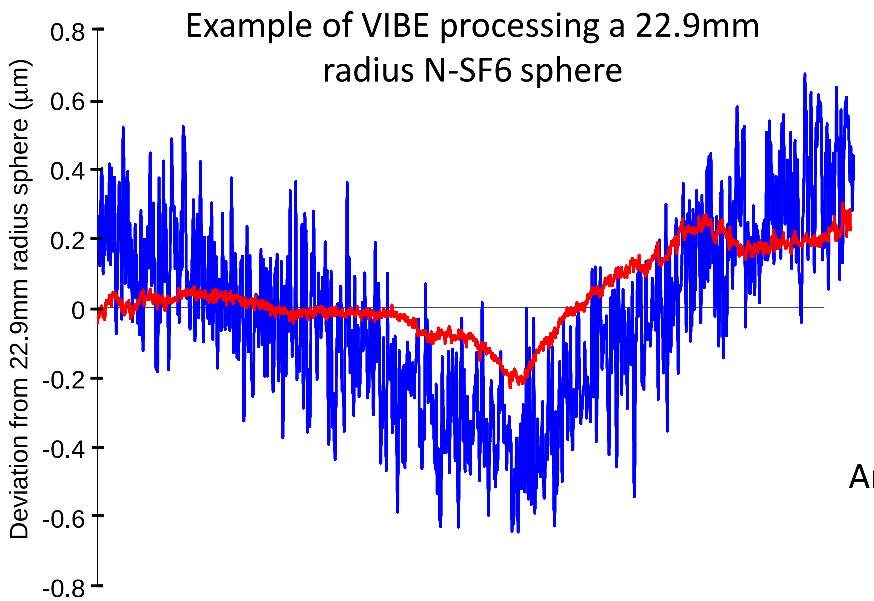
VIBE linear motion with over-stroke

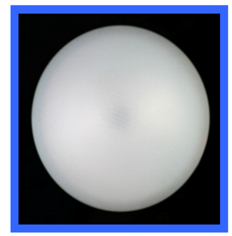




Animation speed and motion has been exaggerated for viewing purposes

VIBE originally intended for pre-polishing glass spheres and aspheres



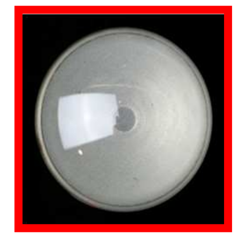


Initial 9T alumina ground surface

Areal surface roughness

P-V: 8517.6nm

RMS: 756.1nm



After 10 minutes of VIBE polishing

Areal surface roughness

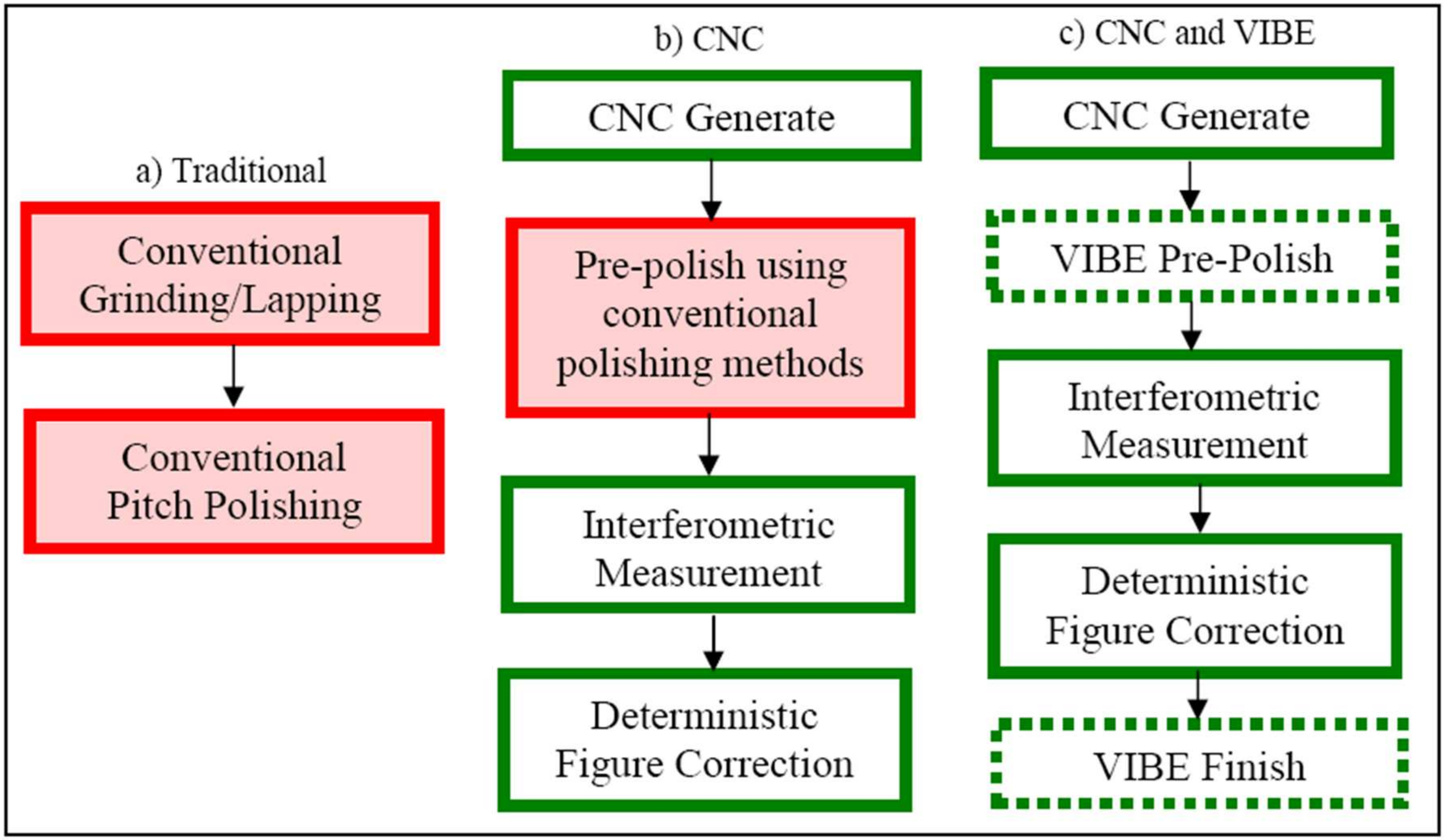
P-V: 12.3nm

RMS: 0.7nm

In just 10 minutes…

– Remove 10µm
– Improve surface figure
– Improve surface roughness by 100x

The role of VIBE in modern optical manufacturing processes



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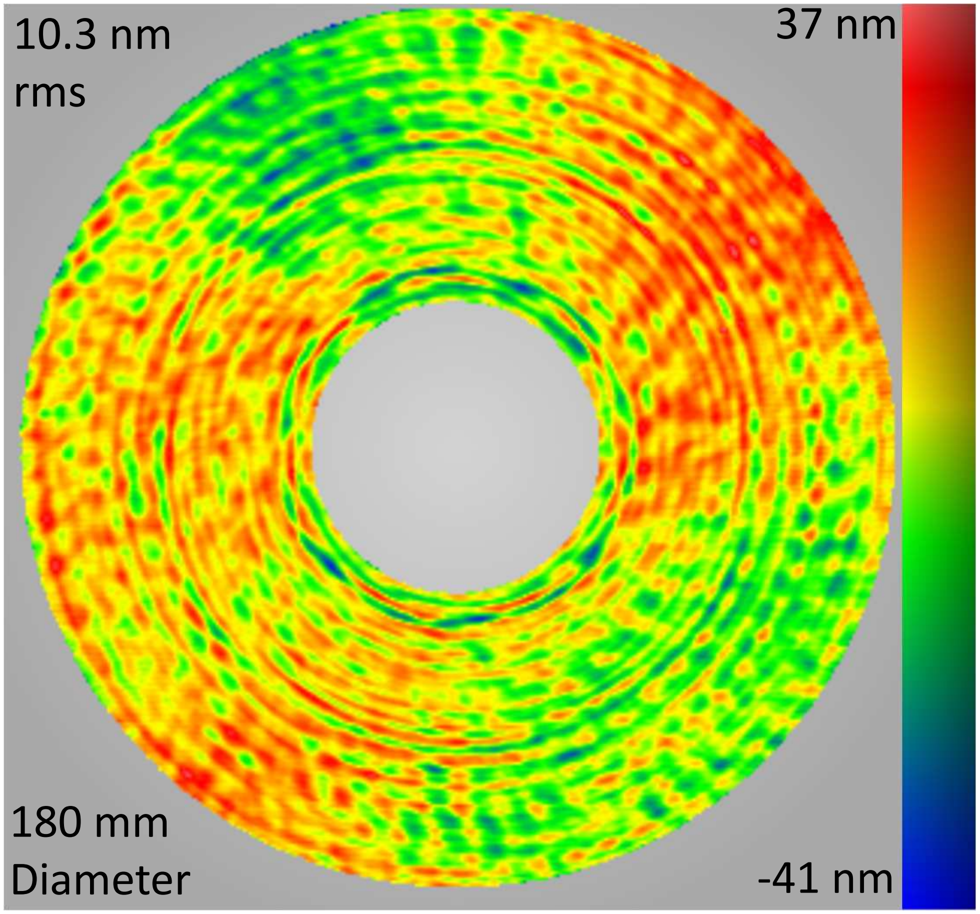
Characterizing Mid-Spatial Frequencies



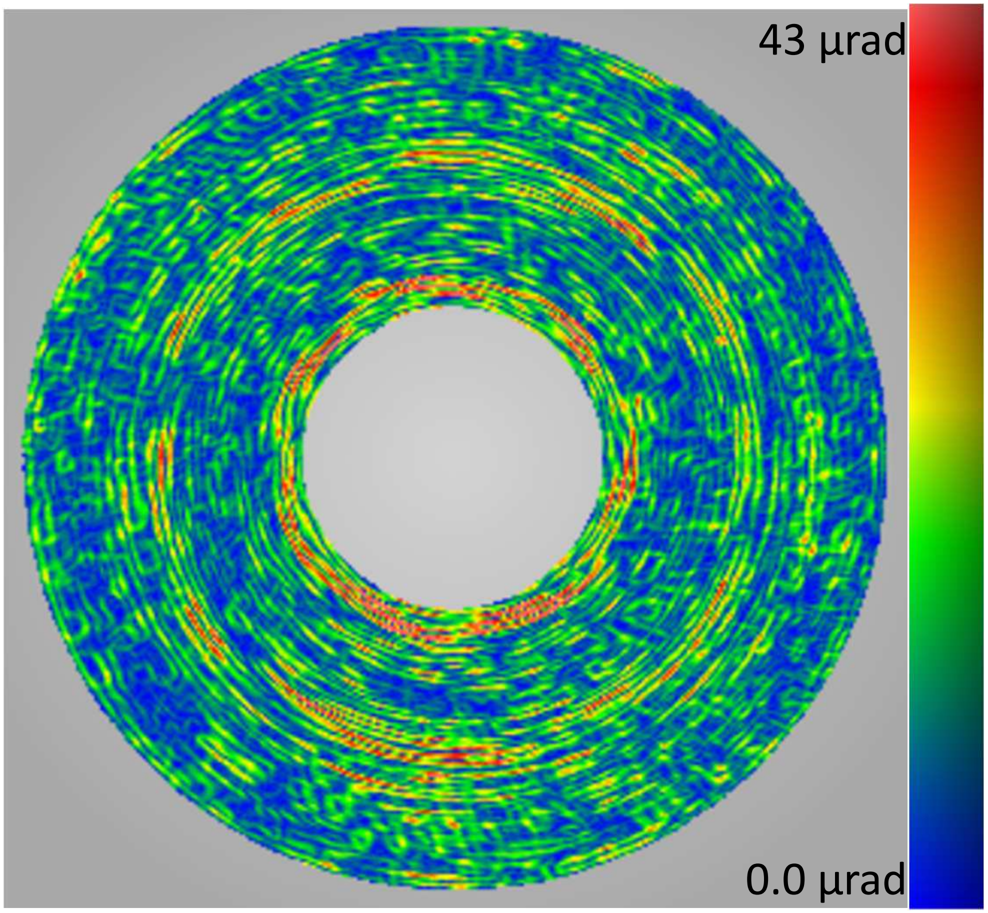
Visual Inspection works well for this part, but it still does not give a quantitative result.

Traditional surface form measurements are not adequate

Possible Methods for MSF characterization:

- Visual Inspection
- Slope
- Zernike Residuals
- Residual after Filtering
- PSD – power spectral density
- Wavelets

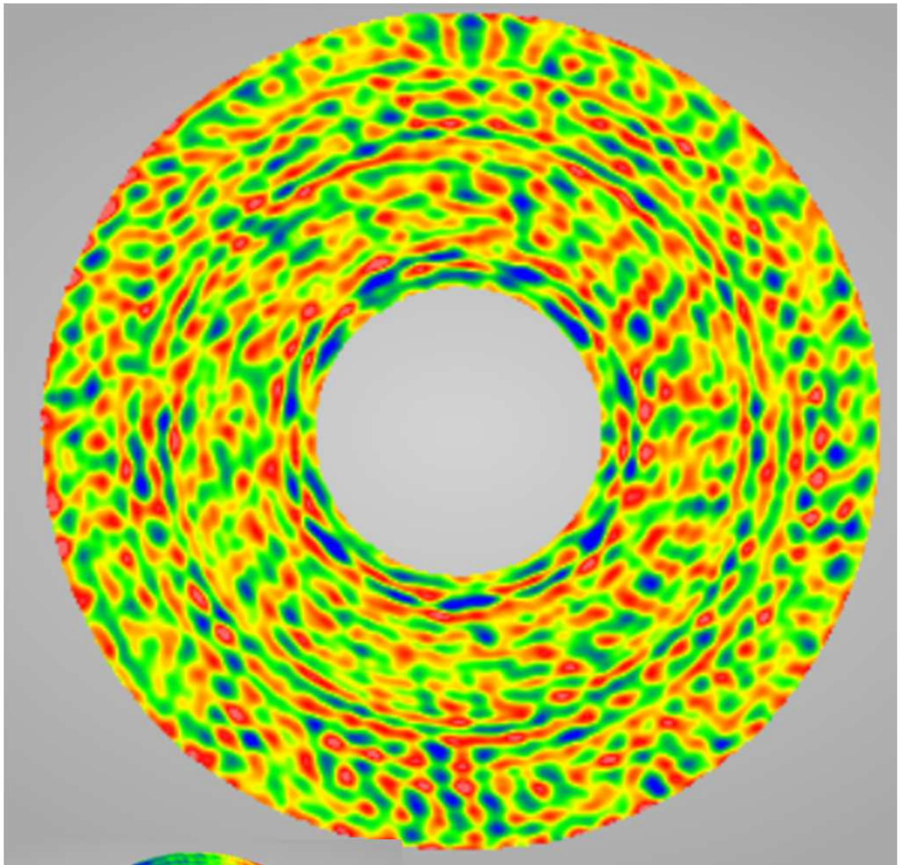
Slope can be a useful characterization

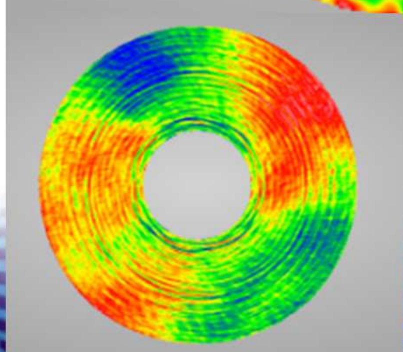


- Specified in either PV or RMS
- Integration length determines feature size
- Default ANSI integration length is 4% of clear aperture
  - 0.5 – 3mm typical for characterizing MSF errors

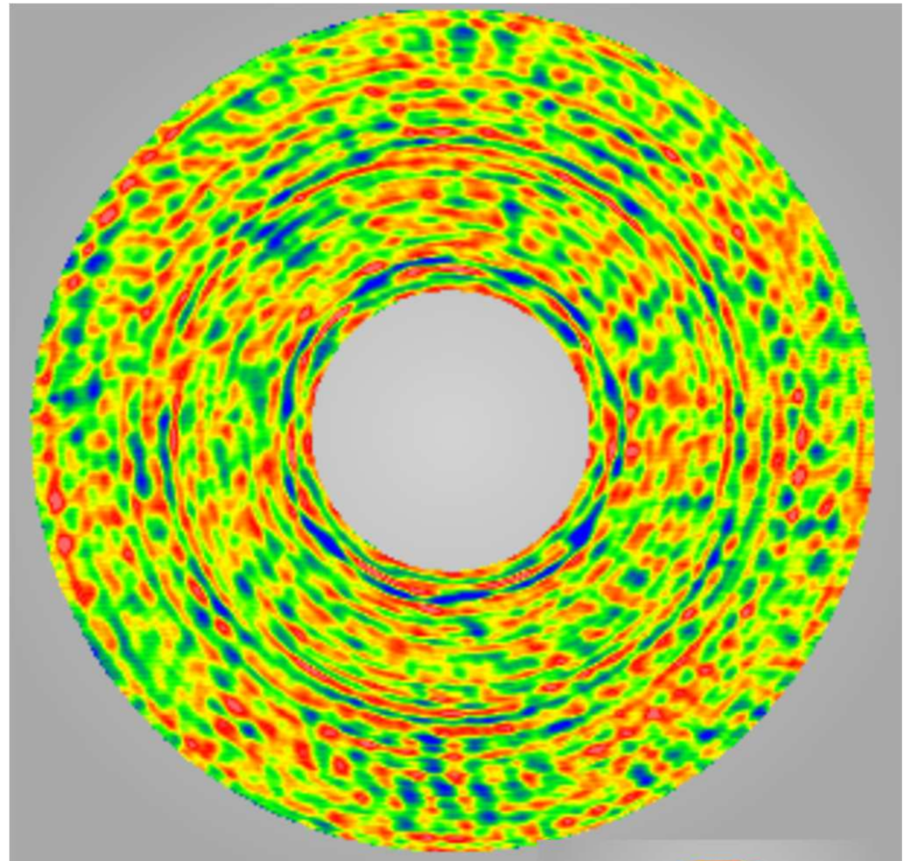
Residuals – RMS, PV of shape after removing form

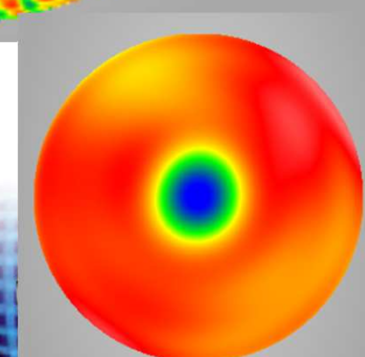
FFT filtering in the range of interest





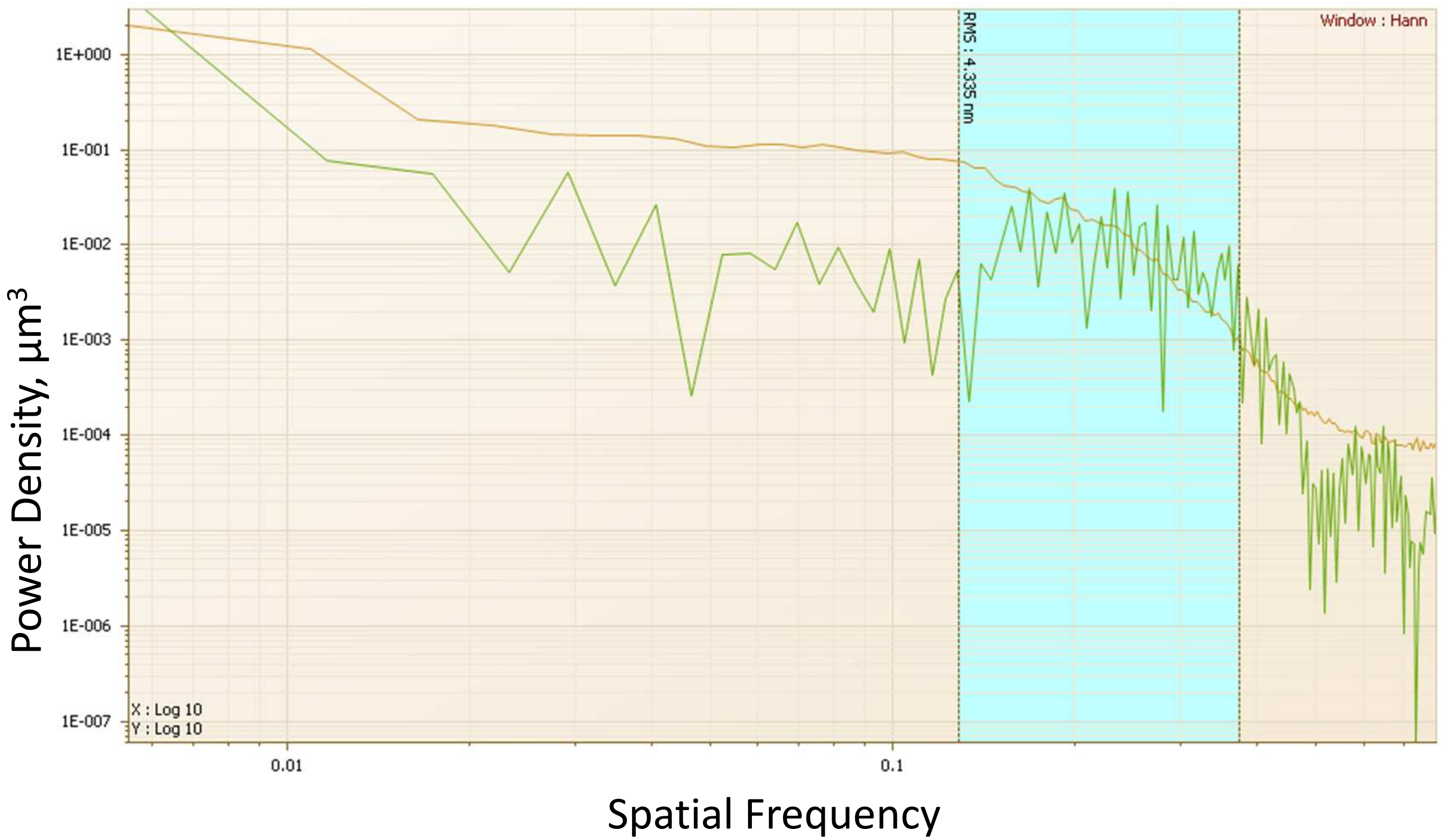
Removed first 36 Zernike Terms





Power Spectral Density

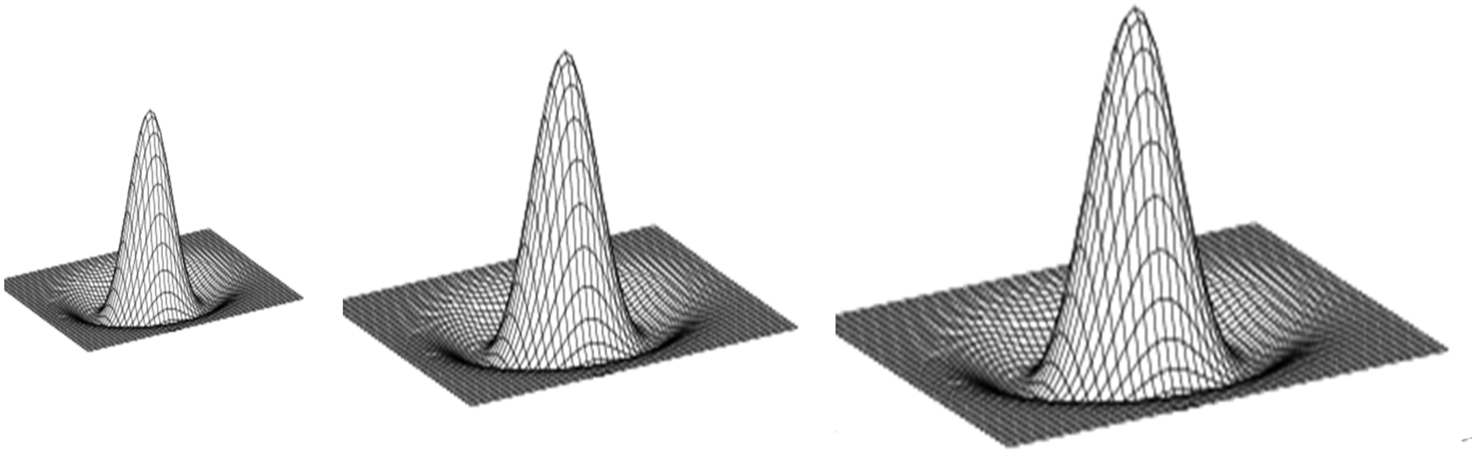
PSD of line traces across sample. Tells you how much energy of sample is in each spatial frequency. Area under curve at frequency of interest is the rms of sample.



Can be difficult to obtain consistent results over various computation methods.

Wavelets

A wavelet analysis tells you the quantity of each wavelet in a signal



A set of wavelets (sized in the area of interest) is formed and using correlation techniques, we can determine how much of that wave is in the height map. That value can be used as the testing parameter.

Additional work to be done in this area

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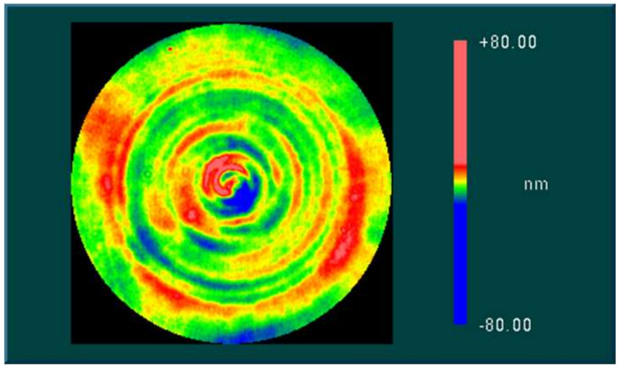
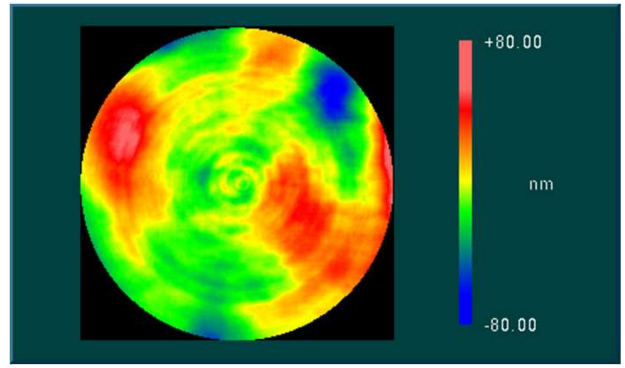
Implementing VIBE to remove MSF errors

- Current status
  - 2010 Phase I – complete
    - Flat surfaces
  - 2011 Phase I – three months into contract
    - Spherical surfaces
  - 2011 – 2013 Phase II – contract signed two weeks ago
    - Robust platform – move toward aspheric and cylindrical surfaces
- Examining different compliant mediums to determine optimum polishing pad composition
  - Material
    - Borosilicate glass
    - Initial surface – sub-aperture figure correction of plano or spherical surface
- Only remove nanometers of material
  - VIBE finishing step completed in less than 60 seconds

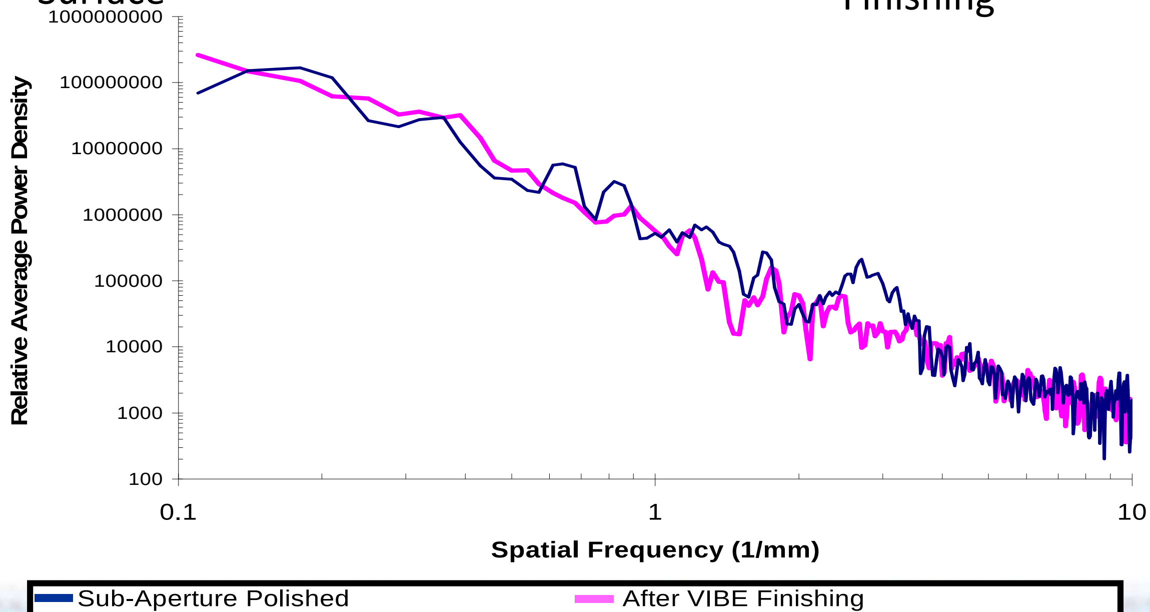
Initial Phase I Results: Reduction of MSF errors on flat surfaces



Initial Sub-Aperture Polished Surface



Surface After 60-second VIBE Finishing



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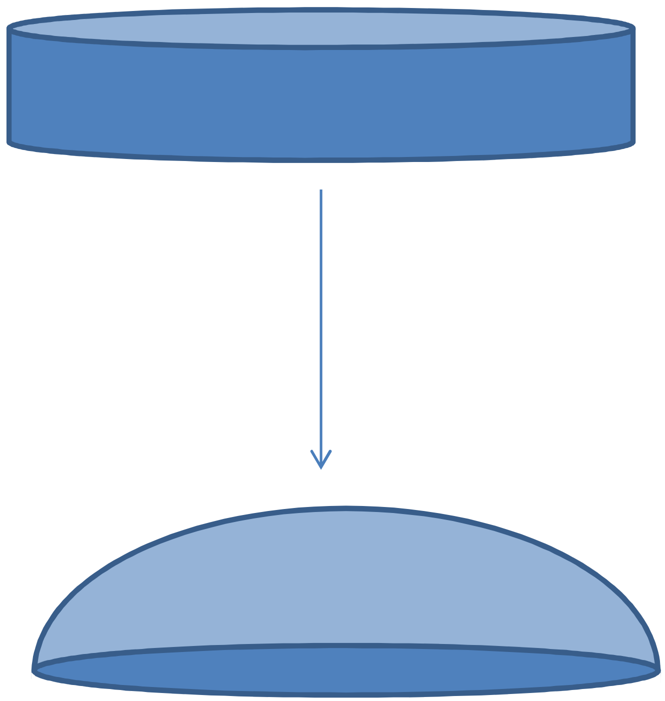
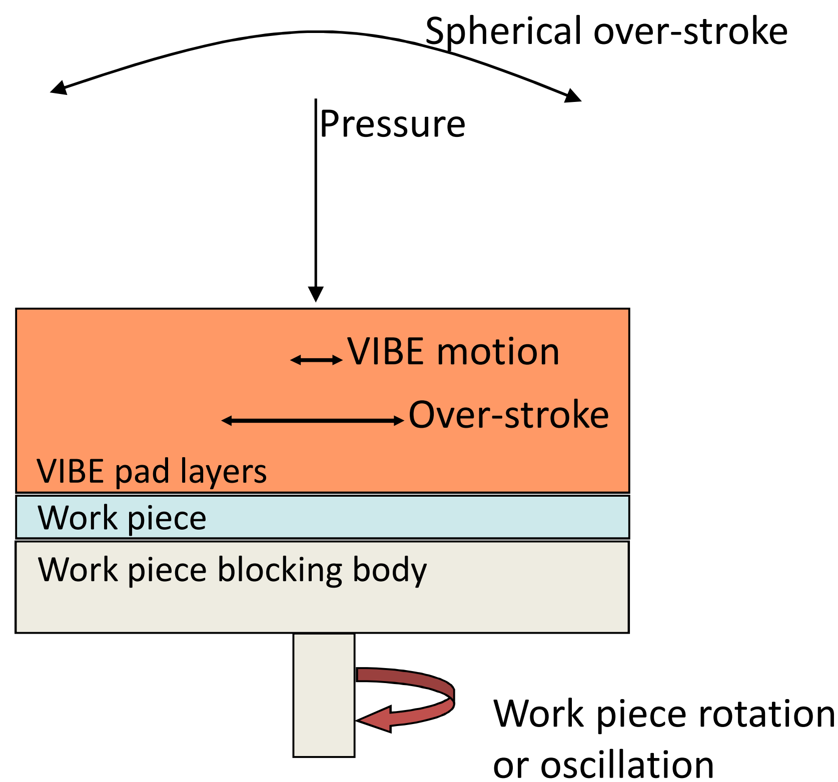
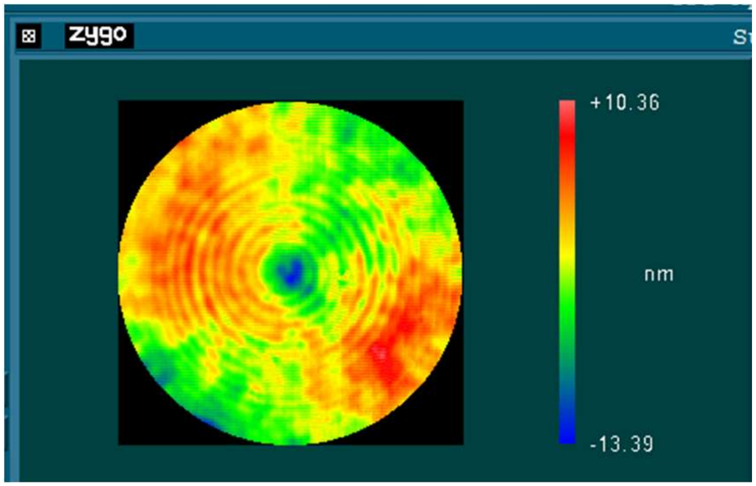
Second Phase I: Removing MSF errors on spherical surfaces

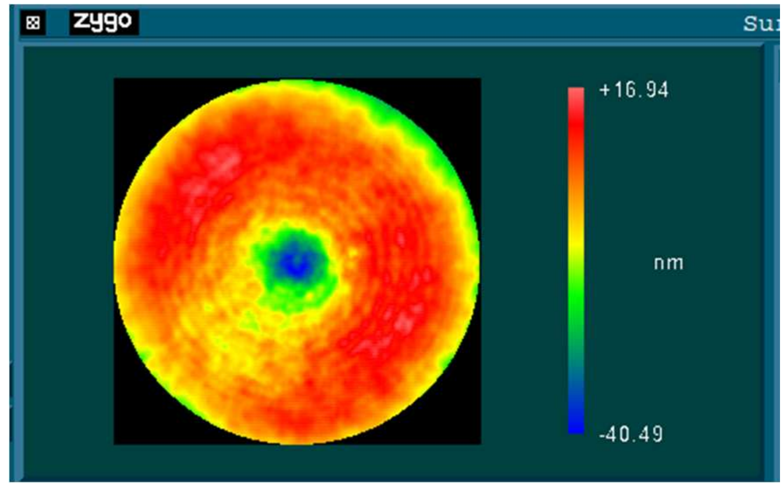


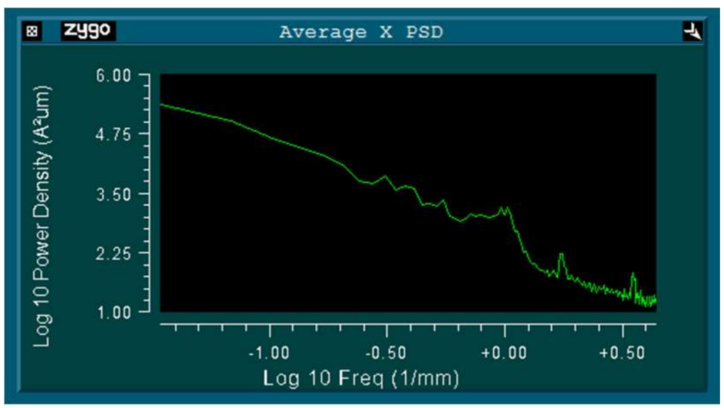


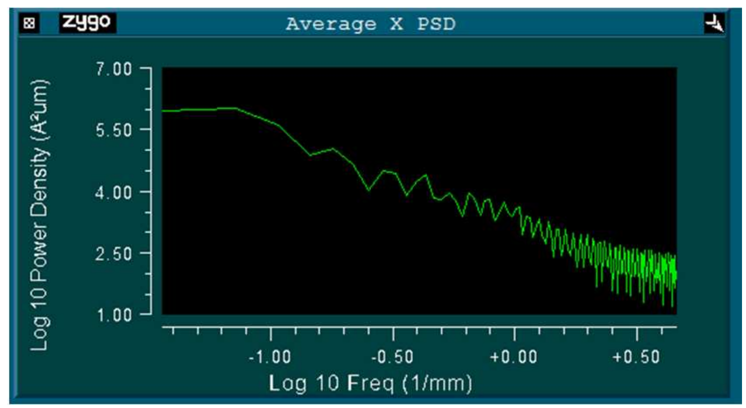
Radius of curvature requires a different motion on test platform

Initial spherical results show reduced MSF error, but form was altered



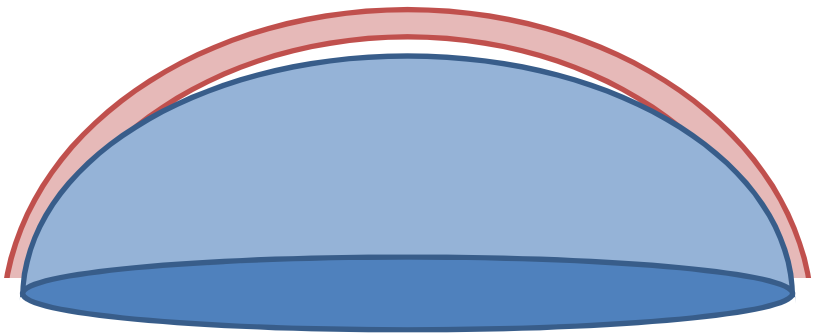




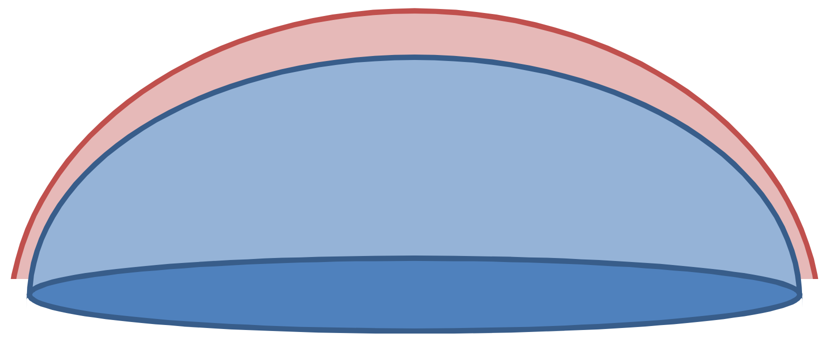


- More compliant lap is necessary

Proper pad compliance necessary to account for form mismatch



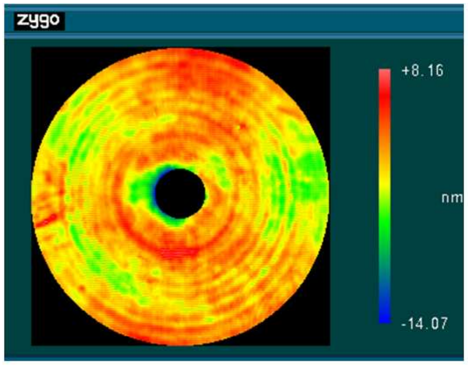
Non-compliant lap

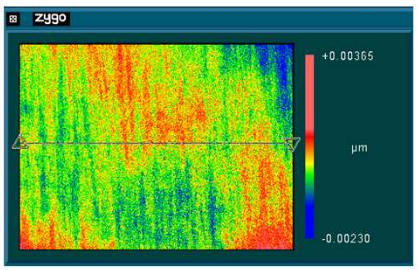


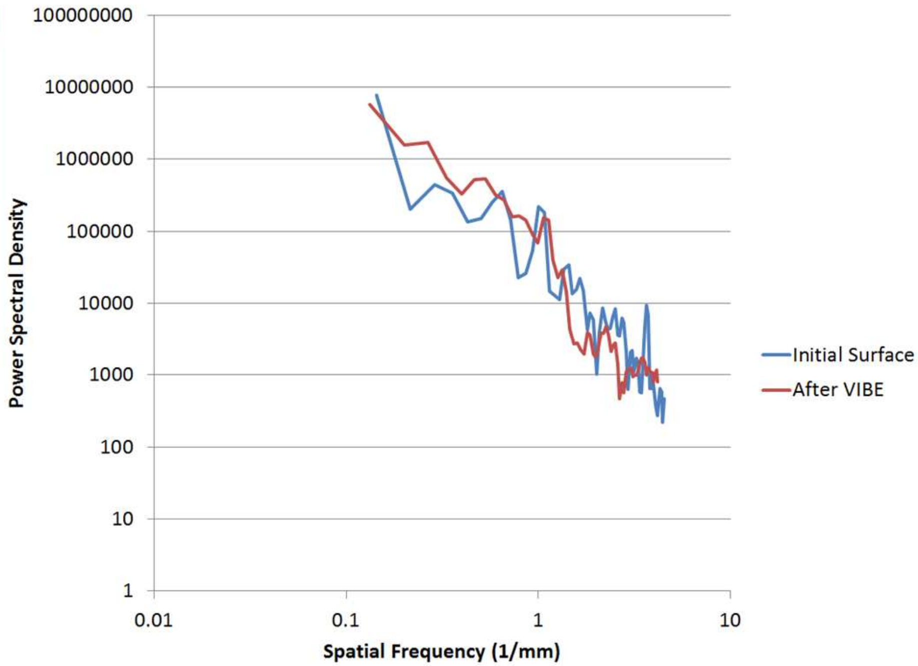
Compliant lap

Higher compliant lap shows more desirable results

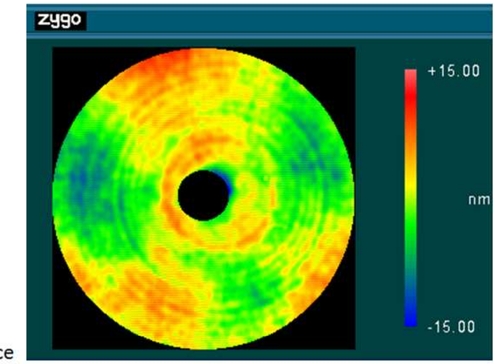
Initial surface

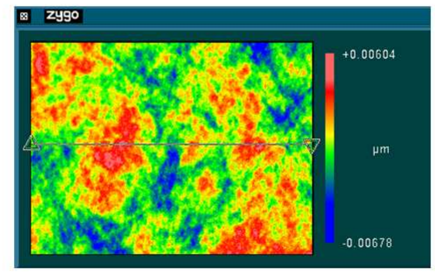






After VIBE





	PV (nm)	RMS (nm)	Peak Slope (wv/cm)	RMS Slope (wv/cm)	Zernike Residual RMS (nm)
Initial	24.8	2.4	0.24	0.054	0.0024
After VIBE	21.6	3.6	0.16	0.051	0.0024

Planned work for Phase II

- Build new platform
  - Flexibility to accommodate multiple surface forms
- Rotational and Raster MSF error removal
  - Spheres
  - Cylinders
  - Aspheres
  - Freeforms
- VIBE finishing to reduce grain decoration on polycrystalline materials
- Interrogate MSF characterization methods

Conclusions and Future Work

- VIBE finishing can reduce the appearance of MSF errors on flat and spherical rotationally polished surfaces

- Continued work on eliminating MSF errors
- Future work: extend technology to spheres, cylinders, aspheres and conformal optics

Acknowledgements

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  - Ron Eng (NASA)
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  - Peter Blake (NASA)

  - NASA SBIR program for funding this work

Small
Business
Innovation
Research

Eliminating Mid-Spatial Frequency Errors with VIBE

Optimax Systems, Inc.
Ontario, NY

INNOVATION

The Optimax VIBE process is a full-aperture, conformal polishing process incorporating high frequency and random motion to *eliminate mid-spatial frequency (MSF) errors* created by deterministic polishing in a VIBE finishing step while maintaining low spatial frequency form accuracy.

ACCOMPLISHMENTS

- Showed feasibility on flat surfaces
- VIBE finishing has been shown to reduce the severity of MSF errors
- We have incorporated repeatable interferometric methods to characterize MSF errors

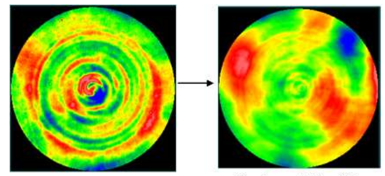
FUTURE PLANS

- Build robust platform
- Extend process to non-spherical shapes

COMMERCIALIZATION

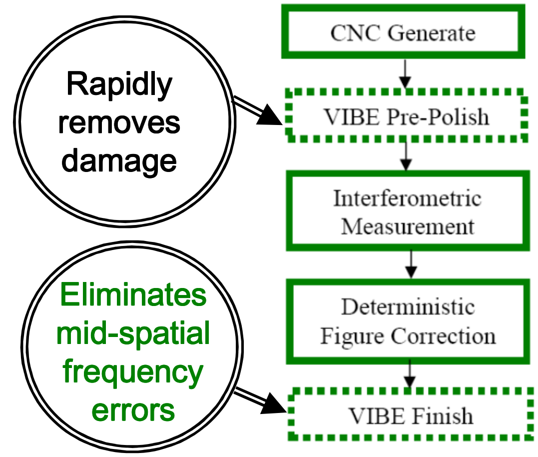
- Optimax VIBE™ Technology
- U.S Patent Number 6942554 B1
- Primary target applications: Optical imaging systems where small angle scatter would reduce performance quality
- Optimax currently provides high precision optics to the aerospace, defense, medical and imaging markets, VIBE technology will enhance our capabilities
- Current customers are designing all spherical optical systems due to Asphere manufacturing limitations (MSF errors)
- MSF errors are formed during deterministic sub-aperture polishing processes. MSF errors cause small angle scatter and flare in optical systems.
  - VIBE Finishing will eliminate these undesirable MSF errors

VIBE Finishing results on a flat surface



Initial Sub-Aperture Polished Surface — Surface After 60-second VIBE Finishing

Introduction of VIBE into today's optical manufacturing process



GOVERNMENT/SCIENCE APPLICATIONS

NASA:

- X-Ray Telescopes:
  - IXO – slumping mandrels, produce surfaces less than 1.4nm rms between 2-20mm spatial frequency range.
- Exo-Planet Imaging Systems:
  - Minimize scatter on primary and secondary mirrors, specifically less than 1nm rms in 4-50 cycles/aperture range

Non-NASA:

- High Energy Laser Systems, EUV Optics (Lithography), Imaging Systems and X-Ray Synchrotron Optics

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Optimax Systems, Inc.
S2.05 Optics Manufacturing and Metrology for Telescope Optical Surfaces; proposal # S2.05-9386 and S2.05-8826
June 22, 2011